Use of a Continuous Wave and Pulsed-Ruby Laser to make Portrait Holograms and Determine Viability for Digital Data Storage

Research Thesis

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Abstract

Holography is a field with the goal of storing 3-dimensional data in a 2-dimensional plane. Looking into future methods of digital data storage as well as media display techniques, holography offers the possibility of communicating large quantities of data through a convenient medium by recording the interference pattern between a uniform plane wave and modulated object wave front, holograms are able to recreate the parallax and depth one views in three dimensions. Using a continuous wave (CW) laser and a pulsed-ruby laser I have made several portrait holograms that are judged by a set of criteria and are compared to determine the strengths of each method to be used in digital holography.

CW laser methods offer full color holograms with low cost equipment that continually transmit information. If the beam modulator changes frames smoothly, the continuity of CW lasers will allow for smooth frame changes. However, CW laser methods generally have lower resolution due to movement during recording and therefore lack the flexibility to record moving or living subjects. Pulse laser methods offer high-resolution holograms with greater depth, and can record moving subjects. The equipment cost is high however, with considerable effort needed to minimize size. With discretely changing digital beam modulators, pulse laser technology will allow for frame changes in between pulses.

1. Introduction

1.1 What is a hologram?

A hologram is a pattern of light and dark fringes typically about 20-35 microns wide on the surface of an emulsified film. The fringes constitute the interference pattern at the surface of the film between a coherent plane wave front (reference beam) and a diffused beam modulated by the transmission or reflection from an object (object beam) as shown in figure 1. If the reference and object beams are both aligned at 45 degrees with respect to the normal of the film plane then the hologram will produce, via transmission or reflection (depends on setup), the original object beam when it is placed back into a reference beam at 45 degrees. In these experiments, the two beams are incident on the same side of the film plane resulting in a transmission hologram that is viewed from the opposite side of the reference beam used for display. More on this setup will be described in the methodology section.

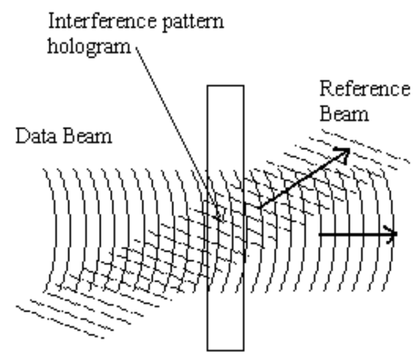


Figure 1

1.2 Holography as a data storage medium

Where the two beams interfere constructively on the surface of the film, electrons are freed from the valence band and boosted into the conduction band leaving behind a bright fringe and a positively charged void in their absence. The dark fringes do not promote this energy state change. A coulomb force will then be acting to alleviate the charge gradient destroying the stored fringe (pixel), however, if the energy provided by the laser alongside a diffusion force is greater than the coulomb force, a permanent electric field from the positively charged regions will be preserved. The disparity of electric field strength in different regions of the medium causes differences in the index of refraction thus leaving behind permanent bright and dark pixels. The energy per unit area required from the laser is determined by the number of fringes per unit length of the recording material as well as the chemical composition of the emulsion.

To retrieve the information stored in the hologram, one needs to direct a reference beam at the same angle used for recording. Due to the local differences in the refractive index, either the transmitted or reflected beam (depends on recording setup) will be a replica of the original object beam. A more rigorous proof of this process is done in appendix A.

The advantages of holographic data storage are that a very large amount of information can be stored per unit area, the writing as well as retrieval process does not need to run one bit at a time but can be processed in parallel allowing for exceedingly fast computing, and lastly the information of a holographic medium is not stored locally meaning that the data can be retrieved from any location on the substrate as long as the orientation of a replay beam is still correct. In theory, a single bit of information can be stored in a block the size of the wavelength of the recording light. This means that approximately 4 gigabits of data can be stored per cubic millimeter with red (632.8nm) light. This is however practically impossible due to flaws in the recording medium and defects/movement in optical components which we see later to be a large issue in producing portrait holograms.

1.3 CW laser holography

One current method of producing holographic images uses a continuous wave laser system such as a helium-neon gas laser. After manipulation of optics to create an object and reference beam, an exposure time is required to allow for the interference pattern to create fringes. The exposure may last anywhere from a second to several minutes depending on film sensitivity, laser power, and size of film/amount of beam diffusion. During this time if the optical arrangement or subject is moved by half of the wavelength of light, the interference pattern will be corrupted, producing a dark hologram if one at all. The issue of stability during exposure poses a practical difficulty in CW laser holography however may be handled with proper optics equipment and handling. Equal beam path lengths must also be maintained in order to ensure spatial coherence at the plane of the film. If the difference in path lengths exceeds the coherence length of the laser, the plane of interference between the beams will occur in a region where the beams are no longer spatially coherent and interference will be weak. Another concern is the maintenance of proper beam intensity ratio. To properly render the information in the hologram, the correct intensity must be allocated to the reference and object beams respectively which depends on viewing methods.

Other gas lasers such as argon-ion and krypton-ion may also be used. The advantage of using an argon-ion laser is that green and blue coherent light can be produced at higher power (about 0.5-1 W). A disadvantage is that these require forced cooling which threatens stability during exposure. A krypton-ion laser spans the whole visible spectrum and can also produce coherent beams outside visible wavelengths. This proves useful in making multi-colored (frequency) holograms which as we will see, lends itself to the flexibility necessary in digital holographic media.

1.4 Pulsed laser holography

An alternative laser system available for hologram production is a pulsed-ruby laser. This type of laser fires 20-40 ns. pulses of coherent light of about 694 nm wavelengths corresponding to a deep red hue with higher energies between 1-20 joules per pulse to expose the film. The gaining medium is a series of synthetic ruby rods that create coherent beams of about one meter long. The optical arrangements for specific types of holograms is essentially the same as with a CW laser however special optical equipment needed to be used due to the presence of higher energy beams. Movement of an object within the time of the pulse adjusts the interference pattern by distances that are orders of magnitude smaller than the fringe thicknesses allowing holograms of moving objects to be clear. The ability to capture data of moving subjects greatly lessens the concern for stability and includes a wider variety of possible scenarios where pulse laser technology can be used. A pulsed-ruby laser also has a significantly longer coherence length (1-3m) which allows for greater depth in the viewing field. With higher energies, larger holograms can be made which allows for more data to be stored because more bits are created in a larger surface of diffused light.

1.5 Digital Holography

Electro-holography is the name given to holographic display systems that use a computer-generated panel of pixels to act as the object beam modulator. A 2-D array of pixels make up an image of fringe patterns that allow light to pass through. In modern practices the pixels are made of liquid crystals (usually lithium niobate) whose refractive index is proportional to the local electric field strength. It is possible to control local E-fields within a pixel array and by adjusting the opacity of each pixel, one can alter the fringe pattern resulting in a new scene (frame). Figure 2

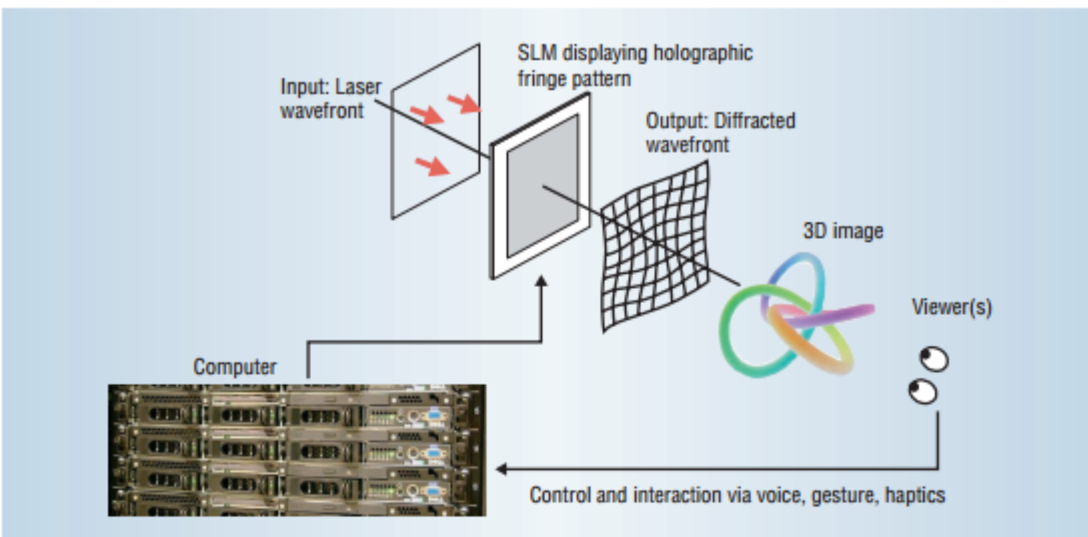


Figure 2

shows a simplified diagram of a digital hologram display. After the beam is diffused and collimated, it reaches the spatial light modulator (SLM), which acts exactly like a finished hologram placed back in its reference beam. The wave front that transmits through the plane now resembles the wave front that has left an object and is reaching the viewers eye.

One of the biggest difficulties in involved with computing interference patterns is the high computing load needed to deliver the information. A horizontal parallax only hologram with the same resolution as an HDTV requires 400,000 horizontal pixels by about 1,024 vertical pixels. The algorithm responsible for calculating the information delivered to each pixel computes simple multiplication and accumulation calculations (MAC's). The amount of data corresponds to 424 giga MAC's or about 2.4 teraflops of floating point operations. This amount of data computation is achieved by the worlds 130th fastest computer. However, these numbers represent a frame change rate of 1 frame per second (fps). To be viewed as a smooth changing screen, the display will need to update at a minimum rate of 15 fps, greatly increasing the computation needed to run digital holographic displays.

1.6 Motivation

Holographic media then offers a unique ability to store vast amounts of data as well as condense 3-dimensional information onto a 2-dimensional surface. Similar to the advent of photography, in its early stages the practice was cumbersome and expensive. However, over time 2-D images became easy to produce, digitize, and stream together to create motion pictures. With this same process in mind, I aim to determine the strengths of current holography methods as candidates for further consideration.

Although modern methods of hologram development do not allow for the dexterity required to store a wide variety of data types, it is possible that through understanding how modern methods produce portrait holograms, we may understand how to move forward using CW and pulsed laser systems to promote holography as a mainstream storage and commercial medium. Specifically, I will be observing characteristics of each laser's display ability and functionality. These characteristics will help shed light on how better to illuminate different digital pixel arrangements with cost-effectiveness in mind.

2. Methodology

2.1 Hologram Criteria

To compare and contrast CW with pulsed laser hologram production, I will be applying three criteria to the holograms:

1. Clarity: Each image will have the qualities of depth, resolution, parallax, brightness, and emulsion transparency all of which act to determine the holograms clarity. The signal to noise ratio is a good way to quantify many of these qualities and will also be considered.

2. Flexibility: An important part in deciding if either laser system serves as a possible research candidate for digital holography lies in the spectrum of possible subjects that can be used with each method. Both CW and pulsed laser systems have constraints on what manipulations can be made and how the information must be rendered from the hologram. By determining if any of these constraints conflict with digitization, we can better choose a candidate method.

3. Cost: I will also give a brief consideration of the monetary cost of each method and of the development that may be required to use each laser system in electronic media.

With the above criteria I will judge the portrait holograms and methodologies.

2.2 CW transmission hologram setup

To make a portrait hologram with a HeNe CW laser, I will be making a laser viewable transmission hologram. Current digital holographic displays are viewed in a position similar to a transmission hologram. For this reason I chose to make transmission holograms. The setup for this type of hologram is shown in figure 3. After the beam is split, either a spatial filter or concave mirror is required to be placed in the path of each beam. This diffuses the beams into cones or columns of coherent light. The reference beam approaches the film plane at 45 degrees with respect to the normal and the object (data) beam that is now modulated by reflection off of a subject, approaches the film on the same side as the reference beam. Once the shutter is removed, the film will be exposed to the beam.

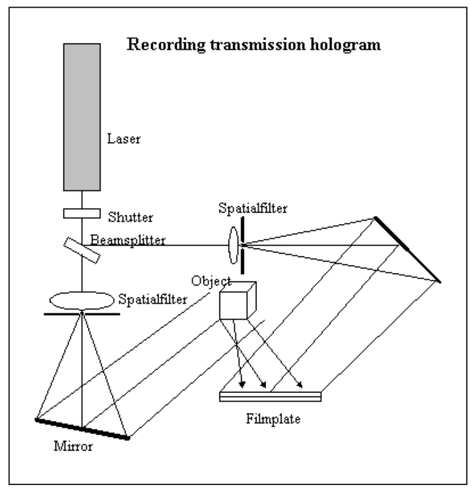


Figure 3

After developing, the hologram can be viewed by placing it back into the original reference beam at 45 degrees. By looking at the film from the opposite side of the viewing beam, the virtual image of the subject can be seen located in its original position. If the film is flipped 180 degrees out of its plane, the real image will be played back. This is pseudoscopic, meaning that the subject is inside out, depth perspective is reversed, and the parallax is reversed.

Figure 4 displays my actual setup that uses a 20 mw HeNe laser. The coherence length of the laser is about 0.5 meters and the resolving power of the film used is about 2000 lines per millimeter.

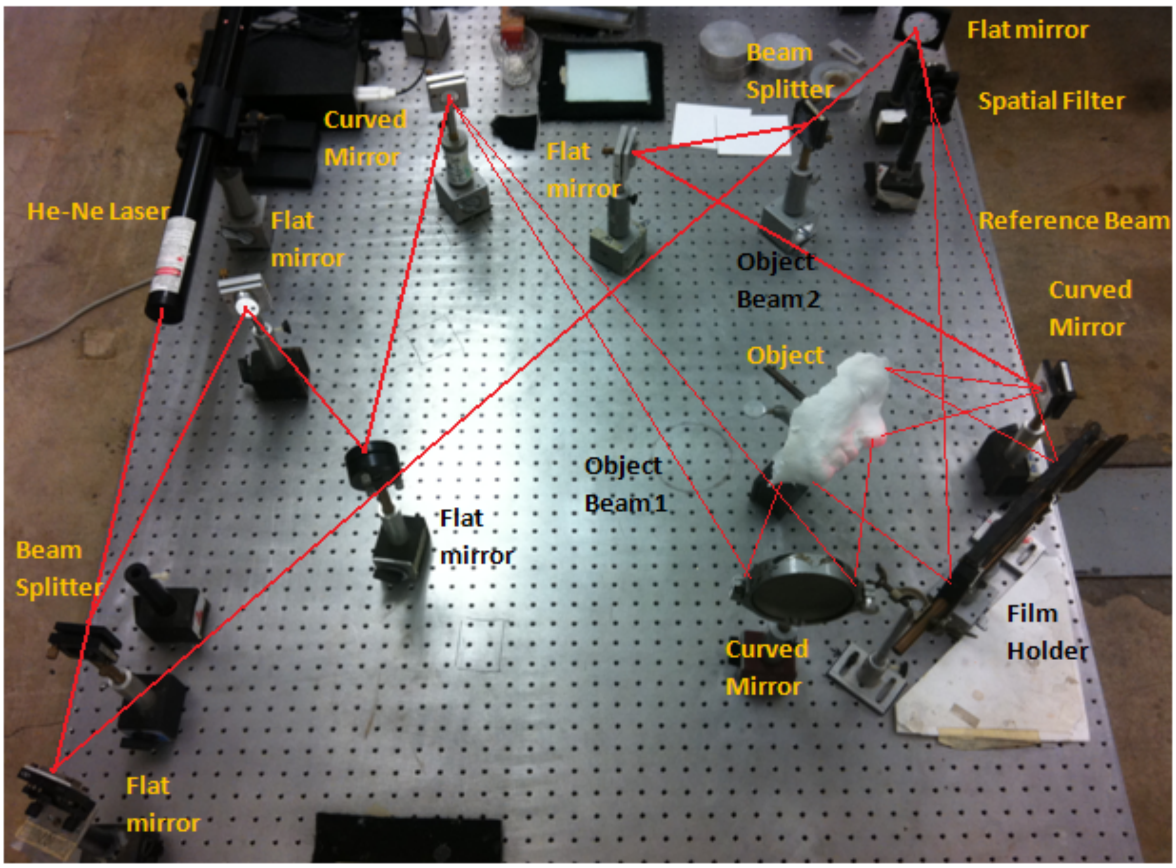


Figure 4

After the beam initially splits, one of the two beams goes on to create one half of the object beam. The other is split again to create the other portion of the object beam and the reference beam that is diffused via a spatial filter. This device is essentially a pinhole that cleans the beam up by focusing only the incident light that is normal to a convex lens. Spurious light waves from imperfections in the optics do not pass through and are removed. This device is unnecessary for an object beam because the modulator (object) creates a unique wave front that is not uniform. Concave mirrors were used to diffuse the object beams. The purpose of lighting the subject from two sides is to get a more desirable lighting of the object.

The subject of this hologram is a plaster cast of my face. To make a portrait hologram with a CW laser, the object must be still on the order of about 60 nanometers over the time of the exposure. Living objects move well over this distance, thus an inanimate representation that can be secure must be used. The inability to use moving objects will factor heavily into the prosperity of CW lasers in digitization as will be seen. The cast is made of a hard plaster material and is supported by metal structures that magnetically attach to the table. After exposure, the film goes through a development process detailed in appendix B.

2.3 Pulsed-ruby transmission master

The second type of portrait hologram is made by a pulsed-ruby laser. As discussed, this laser uses synthetic ruby (aluminum oxide with a small percent of chromium) as its gaining medium. The model of the laser is a Lumonics HLS-2 Ruby Holo-camera. This model uses 2 rods to produce coherent light with a wavelength of 694 nm. With a 1-2 joule pulse, emulsified film with a resolving power of about 5000 lines/mm is properly exposed after 30 ns. This hologram is also a transmission master hologram. Figure 5 shows the layout of the pulse studio.

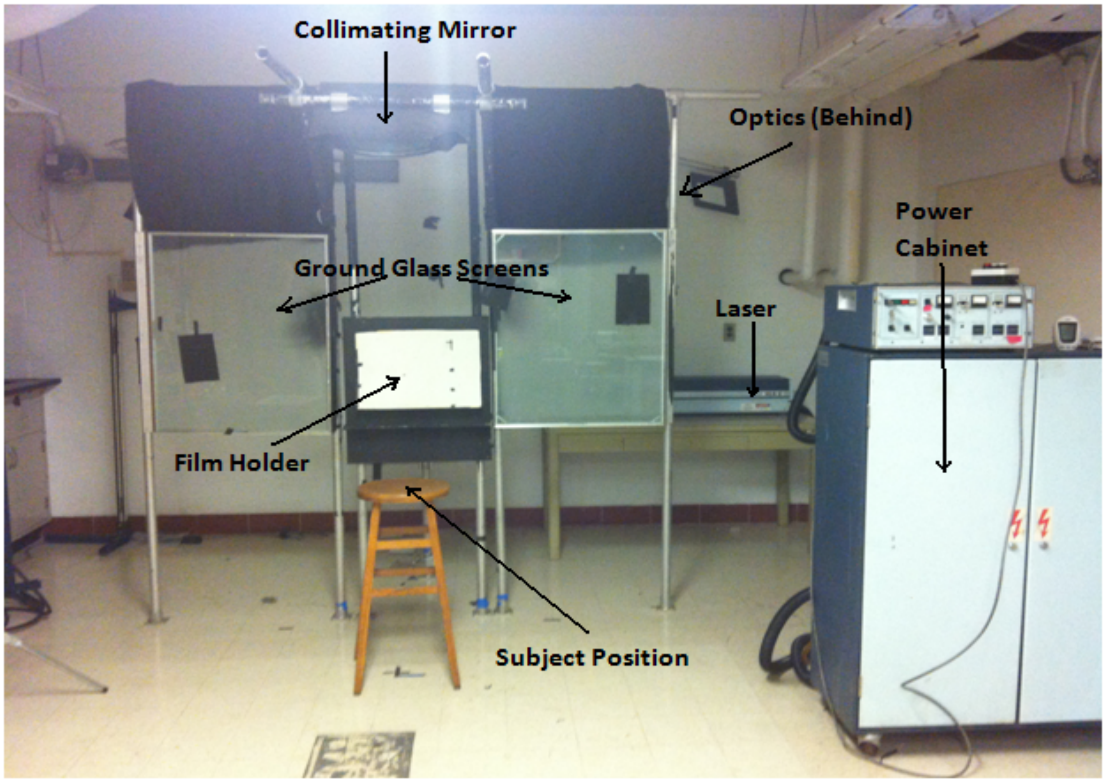


Figure 5

Towards the right side of figure 5 is the power cabinet responsible for holding capacitors and the cooling unit. The laser sits on a table behind the power cabinet and optics. To diffuse the reference beam, a collimating mirror is used. This is essentially a large curved mirror that extends its rear focal point a large distance away and acts to create a collimated beam of laser light. We used a collimated beam because if reflection transfers are to be made of the master hologram, the replay beam should be the conjugate of the original reference beam. If the reference beam were diverging, then the object beam for the transfer would need to be converging which is difficult in practice. We therefore collimate the beam as to use another collimated beam during the transfer process. The object is lit from two sides through two ground glass screens. This allows for a large area to be lit so the subject can be large.

The subject is positioned in front of the film holder where the optics will be slightly adjusted as to shine a guiding laser towards a desired location on the subject. After the laser has reached its appropriate temperature and charge, it is allowed to discharge and expose the film. The developing techniques slightly differ from the film used with the CW laser as discussed in appendix B, but the viewing method is the same.

3. Observations

It is important to note that I have made several CW and pulse laser transmission and reflection holograms. In doing so I altered parameters such as film type, exposure/develop time, laser power, optical arrangement, and subjects to determine qualities that are characteristic of each process on a whole and are not reflective of any one constituent. Certain qualities of the portraits are characteristic of each method only because of modern developing practices that do not appear in digital research. These qualities do not affect candidacy as will be discussed.

3.1 CW laser hologram critique

Figure 6 displays the hologram made with a HeNe laser. Other pictures of this hologram can be found in appendix C. The first criteria to observe from the hologram is its clarity:

- Brightness is adequate to see entire subject and determine contrast. The lighting however leaves undesired dark spots (shadows). This is caused by a smaller beam size specific to the optical setup used to make the hologram.
- Resolution is high enough to distinguish fine detail in the surface of the subject. However in brighter areas, detail is lacking. This is caused by the film being overexposed in some areas and underexposed in others. This is characteristic of CW holograms due to extended exposure time.
- Film emulsion developed with high transparency. Not clear if this is characteristic of CW holograms or pertains to specific developer or film brand. The signal to noise ratio is very high for these holograms. This can be observed by viewing the film where there is no subject. The background is very black meaning the background noise is low. This ratio is in part due to CW holography and developing practices.
- Depth is limited to within a few inches after which the subject becomes dark.
- Horizontal and vertical parallax is limited due to optical arrangement, not necessarily contingent of CW laser holography.

The second criteria to observe is the flexibility of continuous wave laser methods:

- Subject must be stable on the scale of 50-60 nm. This severely limits the spectrum of possible subjects that can be stored. Inanimate, solid objects are the only suitable subjects.

- Manipulation of subject during exposure is possible. This allows for alterations in time of the subject to be recorded. Although small movements will destroy the image, with precision movements one is able to record continuous data flow as opposed to discrete alterations in the subject. This is due to a prolonged exposure time in which an object beam modulator has time to alter the modulation pattern of the beam.
- Some ion lasers (Kr^+) produce coherent beams in multiple wavelengths. This offers the ability to create multi-colored holograms with minimal equipment.

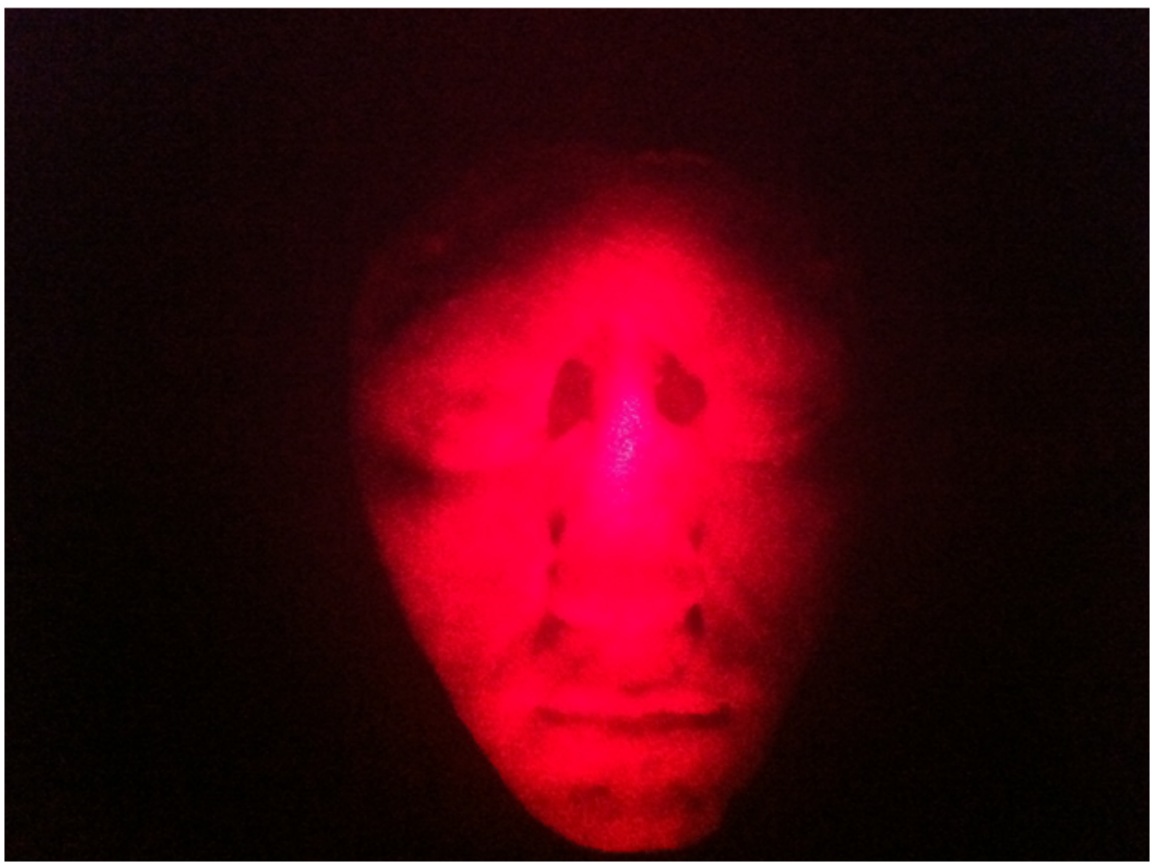


Figure 6

The last consideration to give the CW laser holograms is the cost of their production:

- Total Cost = 1,000-15,000 dollars
- The cost of CW laser hologram production is manageable. Due to some CW lasers being able to create many wavelengths of coherent light, research dealing with true-color holographic media promises to be cost effective.
- CW gas lasers such as the one used in this research have long lifespans of several years if used for hours a day. In a device, this would result in less repair costs.

3.2 Pulsed-ruby laser hologram critique

Figure 7 displays a portrait hologram made with a pulsed-ruby laser. Other images of this hologram can be found in appendix D. Again the first observations are of the holograms clarity:

- The hologram is very bright with sharp contrast. Because the diffused beams are larger, there are no undesired shadows or dark spots.
- The resolution is very high. This may be due to a higher resolution film however it is expected that with an ultra short exposure time that the interference fringes will be sharp. For some subjects, a large viewing angle is required to see the edges of the subject making playback difficult without very large film.

- Film has dark striping in the emulsion after developing. This dims the hologram however it does not affect the subject resolution. The dark spots in the emulsion are not a desirable affect making the signal to noise ratio lower than the CW method. The allowed depth, total brightness, and size however give these holograms high overall clarity. It is unclear whether this is characteristic of pulse laser holography or of the developer used for this hologram.
- Depth is about 1m allowing for a great deal of information regarding the subject's depth to be stored. This quality however will not be noticeable without smaller grain film which is more expensive and easier to destroy

Figure 7

in the process of exposing and developing.

- Parallax angles are large due to wide angle of incident object beams.

Observations of flexibility of pulsed laser method:

- Wide range of subject possibilities. Subject can be still or moving.
- No successful efforts to minimize studio size (laser/power cabinet/optics). This will prove disadvantageous in implementing pulse laser technology into practically sized digital hardware.
- No current method of making true color holograms with pulsed lasers. This is because an efficient gaining medium producing transverse beams in the blue region has not been designed for pulse lasers.
- In digital pulse holography, the spatial resolution of a display is limited by time between successive pulses.

Observations of cost efficiency of pulsed laser hologram production:

- Pulsed-ruby laser systems as well as Nd:YAG lasers have a high cost between 15,000-250,000 dollars. The high equipment costs result in high development costs as well as unaffordable digital devices. This cost does not include optics or film.
- Current pulsing equipment has exceedingly long lifespans as compared to CW gas lasers. This will result in less maintenance costs.

4. Conclusions

When considering the clarity in each method, the biggest difference between the portraits above and electronic displays is that in the latter, silver halide emulsion is not being used but rather liquid crystals are responsible for beam diffraction. During replay, the emulsion serves as a surface with varying opacity to alter amplitude and phase of the beam. This closely corresponds with the function of digital pixel arrays because the amplitude transmittance in both is linearly dependent on the intensity and the index of refraction is controlled. Therefore, the quality differences between CW and pulsed lasers associated with clarity such as brightness and depth in emulsified film can be assumed to remain in electronic displays.

Comparison and contrast of clarity:

- Both methods produced equally bright holograms capable of displaying contrast. However, the smaller size of the HeNe beam made the subject lighting uneven. This problem can be fixed with additional diffuse beam sources however it would require more optical equipment or a larger setup. Similarly, the CW laser needs to be higher energy in order to illuminate large beam modulators.
- Resolution is higher in pulse laser holograms, however; a finer grain film was used for the pulse laser. As stated above, the short exposure time allows for sharper fringes to be created without the disturbance caused by motion. If the same quality film is used for CW laser holograms, the detail goes unnoticed due to destruction of thin fringes by motion. For data collecting purposes, pulsed laser methods allow for more information to be collected. For digital display purposes, if the frame

change rate of the spatial light modulator is high, pulse methods would be preferable to stop blurring between frames.

- CW lasers offer continual data flow which may be preferable if a digital pixel array is made to modulate a light beam via smoothly changing fringes. In this case, the time between pulses in a pulsed laser will act to lower spatial resolution.
- Although there was a clear quality difference in film transparency, namely the CW emulsion developed clear and the pulsed emulsion developed spotty, I will not use this quality to determine if either method can be used in digital data storage. As discussed, the developing process is removed in electro-holography which negates differences in film surface defects.
- Coherence length is much longer in current pulsed laser systems allowing for greater image depth. However, the coherence length is proportional to the actual length of laser which makes modern pulsed-ruby lasers unpractical for digital devices.
- Parallax range is determined by recording angle span and is not necessarily greater in either of the two methods. In the case of pixel array modulators, parallax is determined by how many viewing angles are stored.

The preferable display laser type according to the criteria of clarity depends on the resolution of the SLM and how the modulator changes frames. With smaller pixels a CW laser will blur the fringes between consecutives frames. However, pulsed lasers offer the ability to deliver a short enough pulse of light to stop illumination between frame changes. Most modern pulsed lasers do not have the ability to continually pulse in quick succession for an extended time, however; if this issue were to be resolved, the loss in resolution due to a changing SLM could be managed. If the SLM changes frames smoothly, information will be lost in the time between pulses. Because CW lasers offer a means of continual manipulation of the subject, these would be more suitable for smooth changing SLM fringes.

Comparison of method flexibility:

- As stated, the range of possible subjects that can be holographically stored is much larger with pulsed laser methods as it is not limited to stagnant objects.
- The size of the equipment needed to record and display holograms impacts its ability to be used in electronic devices. The pulsed-ruby laser requires a large power cabinet along with the actual laser that is about 5 feet long. Currently, there is no way to conveniently compress the equipment and maintain the same energy per pulse and long coherence length. However, CW lasers can be made smaller with diodes and still maintain the energy output per unit time increasing the ability to be used in thin displays.
- Pulse laser technology lacks a gaining medium that creates beams in the blue region with high temporal resolution. Without a red, green, and blue laser source, true color holograms cannot be made. CW lasers offer

multiple wavelengths of coherent beams and therefore offer capabilities of true color holograms.

According to the criteria of flexibility, the more suitable candidate method for digital data storage is different depending on whether or not information is being stored or displayed. In the case that holographic data is being created, the high resolution of a quick pulse allows a wider range of possibilities from pulsed laser technologies. If interest lies in displaying rather than recording holographic information, CW lasers promise to deliver full color images with equipment that can be made smaller and is therefore a more suitable candidate.

Comparison of method costs:

- The development cost of each method depends on the cost of the equipment involved. With pulsed lasers, one can expect a laser to cost 10,000 dollars at minimum with additional funds needed for laser components like additional ruby rods (600-1000 dollars) and optics (1,000-10,000 dollars). In contrast, CW lasers offer more manageable costs ranging from 500-5,000 dollars including optical equipment. Therefore, the initial investment required to research CW lasers as a source of digital pixel illumination would be cheaper.
- Gas lasers such the HeNe laser have comparable lifespans to pulse lasers. Although many pulse lasers do not have gas tubes, the longevity is limited by malfunctioning of delicate instruments.

According to the criteria of cost, CW laser research promises to be more cost effective than researching pulse laser holography. CW laser methods will also allow for cheaper optical device components.

5. Comparison with Literature

In this section I will explain current efforts to digitize holographic displays and draw further conclusions on the applicability of the above methods. Figure 8 shows a project done at the University of the Philippines to use a Raman shifter and a Nd:YAG pulse laser to create full color digital holograms. A Raman shifter is a device that makes use of Raman scattering which is essentially inelastic collisions that occur between incident photons and gaseous atoms. This scattering produces multiple output wavelengths and is capable of delivering the three necessary colors (red, green, and blue) to produce full color holography. After the beams are conditioned through spatial filters and neutral density filters, the beam is split to create a reference and object beam. A charge-coupled device is used as a camera to record fringes as digital information.

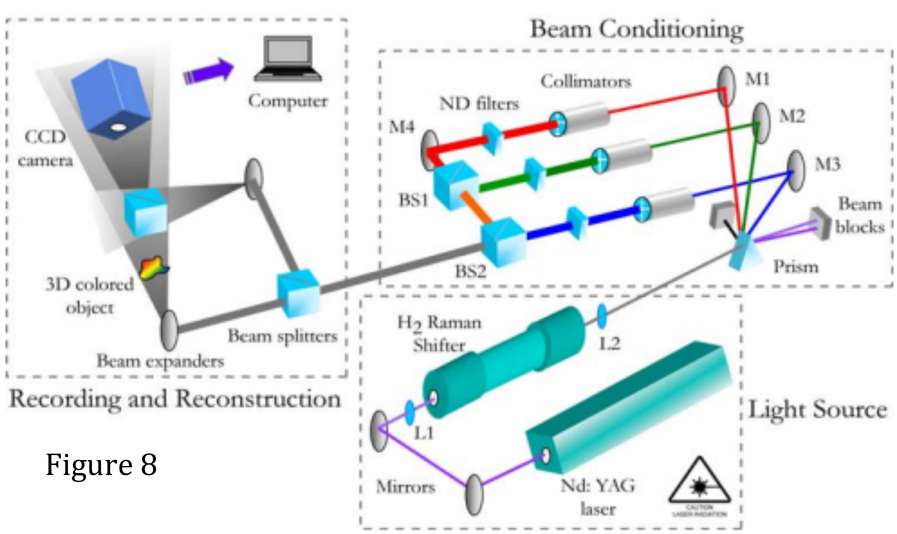


Figure 8

In this experiment, the researchers were able to overcome the inflexibility in multiple color output at the cost of decreased power. According to my conclusions above, pulse laser technology is hampered as a candidate for data collection because full color holography is difficult if not impossible. If the use of a Raman shifter allows for full color pulse holograms to be produced, then pulse lasers offer additional flexibility, and are therefore better candidates to be used in research.

Another research effort done at the Northwestern Polytechnical University uses 3 CW lasers with wavelengths in the red, green, and blue regions to produce full color holograms. A CCD is used to record the interference pattern between an object and reference beam. The CCD moves between regions of the interference plane to record "sub-holograms" one at a time rather than a single CCD recording a largely diffused beam. This is called the synthetic aperture method which limits laser speckle at the recording plane. The setup can be seen in figure 9. Here, one can see the plane in which the CCD moves.

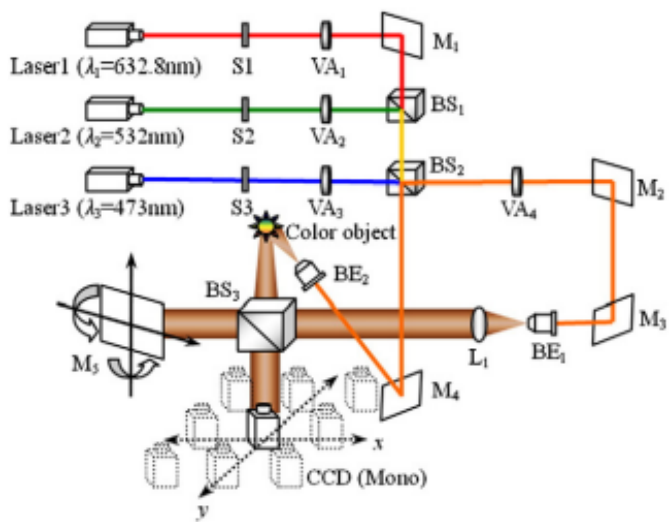
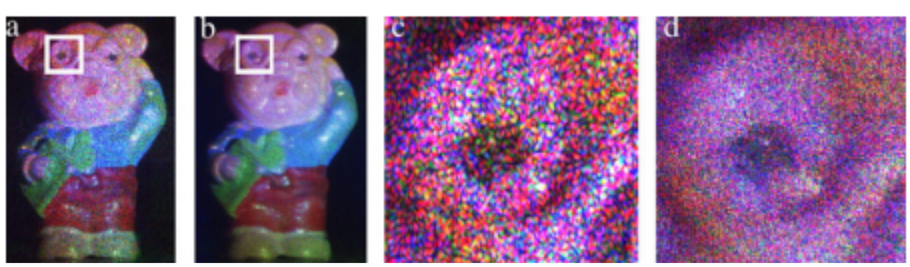


Figure 9

Figure 10 displays the holograms once the separate sub-holograms were reassembled. This experiment allows CW lasers to gain resolution and partially



overcome the deficiencies in clarity that I labeled in the conclusions section. If the synthetic aperture method maintains conveniently short exposure time, CW laser holography will allow for higher resolution imaging and become more suitable for digital data storage research.

A last consideration of current efforts can be given to the use of diode pumped solid-state (DPSS) lasers. DPSS lasers are often CW lasers that use a diode as a pump source to pump a solid gaining medium such as synthetic ruby or neodymium crystal. The quality of the exiting light then does not depend on the pumping light as is the case with other diode lasers. Figure 11 shows the general structure of a DPSS laser where two types of crystals within an etalon can be seen to comprise the gaining medium. These lasers offer high power that is easily compressible.

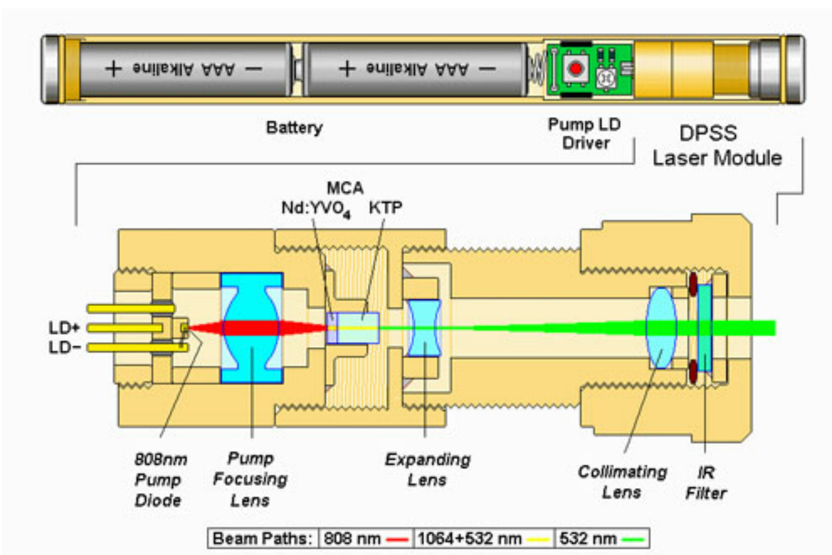


Figure 11

However, the cost of such lasers is usually very high (roughly 2,000-30,000 dollars) which make them difficult to acquire. If these systems were to become cheaper in the future, CW laser holography would stand as even stronger candidate for digital display due their ability to provide continuous high quality, high energy beams in small equipment.

Appendix A

The following is a proof of the reconstruction process of a hologram wave front.

According to the grating equation:

$$d \ \sin\theta = m\lambda$$

where d is the grating (fringe) spacing, m in this case is 1. The spatial frequency (ξ) is then 1/d:

$$\xi = \frac{\sin\theta}{\lambda}$$

So where y is vertical in the plane of the film and x is horizontal in the plane of the film, the complex amplitude of the reference beam is:

$$r(x,y) = re^{i2\pi\xi x}$$

In the above expression, only the phase varies across the plane due to differing path lengths. The film plane is tilted with respect to the beam such that beam lengths differ in x, not in y. To write the complex amplitude across the surface of the object beam, both phase and amplitude variation must be considered.

$$o(x,y) = |o(x,y)|e^{-i\phi(x,y)}$$

where $\phi(x,y)$ is a function characteristic of the subject. If the intensity of the beam is the amplitude times its conjugate then the intensity across the film during exposure is:

$$I(x,y) = |r(x,y) + o(x,y)|^2 = r^2 + |o(x,y)|^2 + 2r|o(x,y)|\cos[2\pi\xi x + \phi(x,y)]$$

In the case of digital pixel arrays or photographic emulsion, the ratio of transmitted amplitude to incident amplitude called, amplitude transmittance, upon playback is linearly dependent on the intensity:

$$t = t_0 + \beta TI$$

where t is the amplitude transmittance, $t_0$is background transmittance, β is a parameter defined by current developing practices, T is the exposure time, and I is the incident intensity. Plugging in the incident intensity:

$$t(x,y) = t_0 + \beta T r^2 + \beta T|o(x,y)|^2 + \beta T r|o(x,y)|e^{-i\phi(x,y)}e^{-i2\pi\xi x}$$
$$+\beta T r|o(x,y)|e^{i\phi(x,y)}e^{i2\pi\xi x}$$

When the hologram is illuminated by its original reference beam, the complex amplitude of the transmitted wave is:

$$u(x,y) = r(x,y)t(x,y)$$

Plugging in values for r and t:

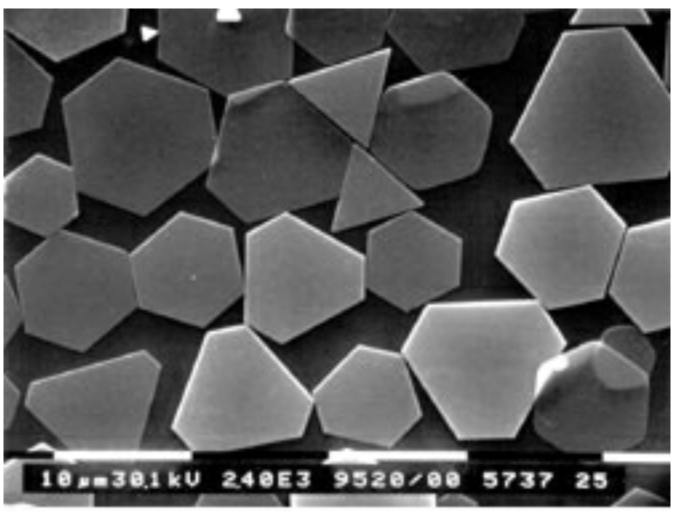
$$u(x,y) = t_0' r e^{i2\pi\xi x} + \beta T r|o(x,y)|^2 e^{i2\pi\xi x} + \beta T r^2 o(x,y) + \beta T r^2 o^*(x,y)e^{i4\pi\xi x}$$

where t_0' is $t_0 + \beta T r^2$. The four terms on the right side of the above equation represents different transmitted beams. The first term is the directly transmitted plane wave reference beam. The second represents a halo surrounding it. The third term is a replication of the object wave with a factor of $\beta T r^2$ acting as a magnifier. This is the virtual image that displays the subject in its original position when viewed. The fourth term is the conjugate of the virtual (orthoscopic) image and is therefore the pseudoscopic real image.

Appendix B

The following explains holographic emulsion and details the developing process used for this research and current practices.

The emulsion used in modern holography consists of a gelatin layer coated on the surface of a substrate (plastic, glass, paper) with light sensitive compounds suspended in it. The light sensitive material is a colloidal silver that consists of silver halides (AgBr, AgCl, and AgI). The halide crystals are suspended in the gelatin layer as shown in figure B.2. When the emulsion is exposed to light, the halide crystals are reduced to metallic silver clusters that make up a latent image. After exposure, the film is placed into a developer which reduces the remainder of the silver halide crystals with latent image centers to metallic silver leaving behind a dark image where the latent image previously existed.



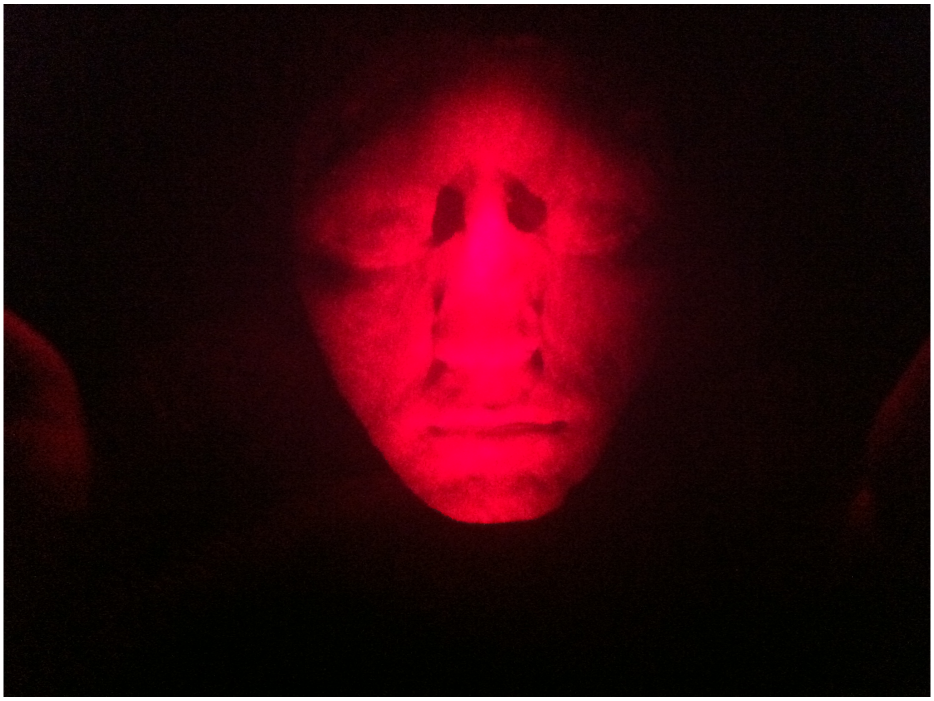
Electron micrograph of tabular grain emulsion

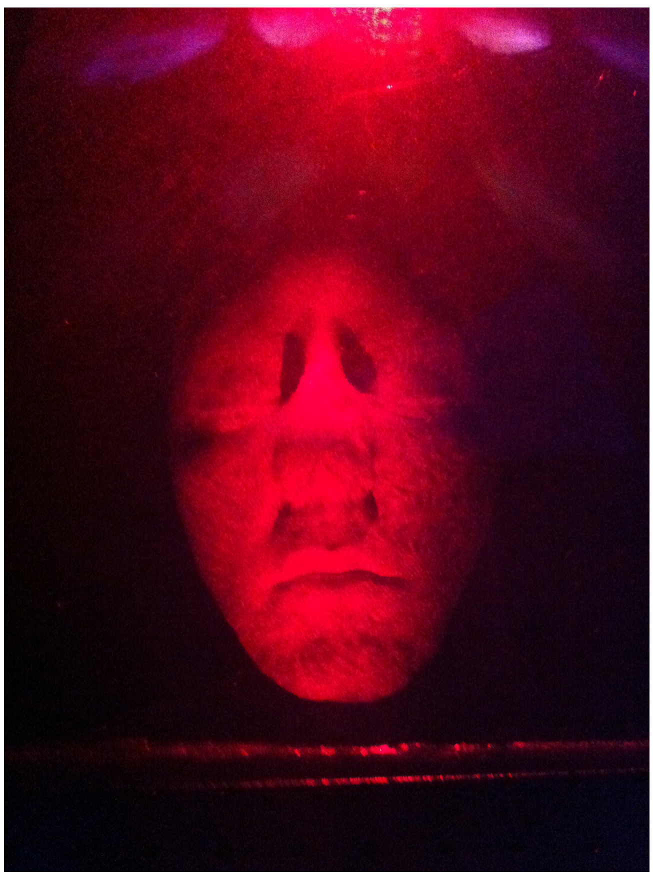
Figure B.1

After development, the film is stopped either by a long rinse to remove the developer or placed in an acetic acid stop bath which nullifies the developing process. To remove the remaining silver halide, a fixing bath is applied to the film. This is called bleach and is comprised of ammonium sulfate and Ethylenediaminetetraacetic acid (EDTA). A wash is necessary after fixation to remove chemicals from emulsion surface. The hologram can now be viewed. The chemicals used in my research were mixed with molarities that made developing time 3 minutes, stop bath 2 minutes, and the bleach was applied for as long as necessary to make the film transparent.

With smaller grain size, the image is sharper and allows for a higher signal to noise ratio. However, this type of film is heavily subject to the developing practiced discussed above which often results in hazy or foggy film.

Appendix C





Appendix D

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